MASS TRANSFER IN STIRRED GAS LIQUID CONTACTORS

By

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CERTIFICATE OF APPROVAL

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A project dissertation submitted to the

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Approved by,

…………………………….

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May 2014

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(MUHAMMAD AFZAL BIN AZMI)

ABSTRACT

The knowledge of gas liquid mixing is a vital part of chemical engineering discipline. The application of gas liquid dispersion is widely practiced in the industries nowadays where the gas liquid mass transfer rate is the main interest in the process. In order to enhance the mass transfer the volumetric mass transfer, the stirred tank contactor vessel is used in the industries as well as in the lab. However a problem arise when the parameters that affect the rate of mass transfer is not well studied and understood which can lead to bad operation of the gas liquid mass transfer in stirred contactor.

Prior to the problem, three main parameters affecting the volumetric mass transfer in the gas liquid stirred contactor will be studied which is the impeller speeds and the flow rate of the gas flowing into the vessel. The proposed experiment will be conducted by varying the operating parameters. In studying the effect of gas flow rate to the mass transfer rate, the impeller speed and the power of the impeller is treated as the fixed variables and vice versa.

ACKNOWLEDGEMENT

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ABBREVIATION AND NOMENCLATURE

a= mass transfer interfacial area(m^2/m^3)

C_{air}=Maximum oxygen concentration in liquid(mg/L) or (mg/m^3)

C_i=Initial oxygen concentration in liquid(mg/L) or (mg/m^3)

C_o=Initial concentration of the oxygen in the gas(mg/L) or (mg/m^3)

C_L=Equilibrium concentration in the liquid

C1=Impeller tip speed constant.

D=Diameter of impeller (cm)

D_b=Diameter of the bubble(cm)

ξ=Gas hold up

k_Ga =Mass transfer coefficient of the gas,k_Ga

k_La= Mass transfer coefficient of air to liquid

N=Impeller speed (rpm or rps)

N=Mass transfer rate(mol/second)

ND=impeller tip speed (cm/s)

N_C=Critical impeller speed (rpm)

Q_g=Gas/ air flow rate(L/min)

T=diameter of the vessel(cm)

V=Volume of liquid (cm^3)

1. INTRODUCTION

1.1 Background of Study

This research paper is basically related to the gas liquid mass transfer in the stirred vessel system. The gas to liquid mass transfer is one of the applications which are mostly used in many processes in industries. Among the industries that implement the concept of gas to liquid mass transfer include the food and petrochemical industries. In order to evaluate the rate of mass transfer the value of volumetric mass transfer coefficient, k_La need to be calculated. The purpose of this experiment is to study the effect of the operating parameter to the k_La values in the stirred gas liquid contactor. The experiment will be conducted using the stirred contactor of diameter, T 28.5 cm and 6 cm diameter of the impeller, D. The parameters that will be tested as the variables which is 1) The effect of gas flow rate 2) The effect of impeller speed

1.2 Problem Statement.

One of the important elements of the chemical engineering operation is the application of gas liquid mixing. Several major industrial operations like oxidation hydrogenation and biological fermentation, adopt the application of gas liquid mass transfer (Harnby et al., 1985).Prior to that a study of the mass transfer in stirred gas liquid contactor should be performed in order to provide a better understanding on the mixing and dispersion of gas into liquid. Without a good understanding of the process it will lead to the poor operation of the industrial operation and the opportunity to optimize the mass transfer will be lost. Most of the time the practice of mixing operation is multi-faceted where the agitator is used to perform many critical task in the fermenter operation. Hence It is important for the process engineer to take account all the factor affected by stirring in fermenters , which include the oxygen transfer, surface cooling ,air dispersion power drawn as a result of aeration as well as biological stability (Harnby et al., 1985).In this proposal the agitation speed, power and gas flow rate is studied in order to understand its effect on the mass transfer.

1.3 Objective

The objective of the research paper is to study the mass transfer rate of the stirred gas-liquid contactor and how it will be affected by several operating parameter which include, the frequency of the impeller stirring speed, N (1/s) and the gas flow rate Q_g(L/min). In order to run this research, an experiment will be conducted. The contacting vessel is used where the gas is introduced at the bottom to form bubble in the vessel. The mean diameter of the bubble is one of the factor that will affect the gas liquid interfacial area per unit volume a,(m^2/m^3)as well as the gas hold up that will be further discussed in the literature review. It is desirable to have a smaller diameter of the bubble upon contact in the vessel as it can significantly increase the gas-liquid interfacial area per unit volume; a. Gathering information on the characteristic of the bubble in the bubble column is a vital step as the performance of the stirred gas liquid contactor depend on the size of the bubbles, rising velocity of the bubble as well as the velocity profile of the bubble (Shah et al., 1982).

1.4 Scope of Study

In this experiment the air-water system will be used to study the gas-liquid mass transfer. Water will be used as the contactor liquid and the air as the gas where the air will be drawn into the vessel using the air compressor.

The scope of the research is to find the effect of the following variables to the K_La values:

1. Stirring speed,N(rpm)
2. Gas flow rate.,Q_g (Liter/m)

2. LITERATURE REVIEW

2.1 Stirred Tank Gas Liquid Contactor

Stirred gas-liquid contactor is a vessel which is used to provide a contact between the gas and the liquid in order to serve as a medium to provide the mass transfer. The gas will be withdrawn into the contactor vessel through the vessel from the bottom of the contactor**.** According to Treyball(1980) the best method to operate the gas liquid contactor vessel is by sparging the gas below the impeller at the bottom of the vessel using a ring shaped sparger where it has the same or smaller diameter with the diameter of the impeller used in the vessel and the hole should be provided at the top of the contactor vessel. When the time of between the gas bubbles and liquid is relatively large, deep vessel is preferably used. Meanwhile in order to maintain a large interfacial area for the gas to liquid mass transfer, multiple impellers are used to redisperse gas bubbles as a result of the bubbles coalescence. The interfacial area which is denoted by the symbol a in this proposal is basically evaluated per unit volume and the unit for it is m^2/m^3. It will be further discussed and derived in the theory of the literature review. The value of the volumetric mass transfer coefficient is the variable that is going to be calculated in the gas-liquid mixing process.

Besides that in the operation of processiing plant in every part of chemical industry,where the mixing process play an important role, the mechanically agitated contactors are the vital equipment for the operation. In analyzing the literature of characteristic and performance of the ga sliquid contactor,a significant data can be found.In many application of gas liquid mixing nowadays,gas liquid contacting vessel with six blade Rushton disc turbine, gas sparger, and four baffles is usually used but in the term of power consumption and top to bottom mixing these contactors have some disadvantages where high power consumption is required and the top to bottom mixing are poor (Jafari and Mohammadzadeh, 2004).In the other study it is found that the industry frequently use the mechanically agitated aerated vessels for the purpose of gas liquid mixing. Multiple impeller contactors is able to utilize higher mass transfer rate and because of the reason it is more widely used. Besides that the parameters like power consumption, gas hold-up, dispersion mixing intensity and volumetric mass transfer coefficient is required to design the stirred gas liquid contactor vessel (Moucha et al., 2003).

2.2 Previous Study

In conducting this project it is important to refer previous studies regarding the gas liquid contactor done by the previous researchers in order to grasp a better understanding on the principle of gas liquid contactor. As examples Brown et al., have studied the liquid phase mixing model for the stirred gas liquid contactor while Koetsier et al., have studied the mass transfer rate in a closed stirred tank gas liquid contactor. In studying the gas liquid contactor system, it is important to consider the effect of the impeller on the gas liquid mixing .The research on the multistage agitated contactor with the co-current air flow where the gas hold up and liquid phase mixing have been done (Zhang et al., 2006). Besides that a scale up study for various impeller types in multiple impeller system have been performed where the volumetric mass transfer coefficient is the main parameter of interest (Labik et al., 2014). Other than that the power of the impeller is also one of the factors affecting the effectiveness of the gas and liquid mixing process and the design of the multi impeller system based on the power and mass transfer correlation have been presented (Linek et al., 2012).

2.3 Mass Transfer Theory

Based on the principle of the mass transfer, the mass transfer rate, N (mole/second) is equal to the value of the mass transfer coefficient; k (m/second) multiplied by the variables value of interfacial area of the gas bubbles, a (m^2/m^3), the volume of the liquid

V (m^3) and the difference between the gas and liquid concentration. The equation is denoted by the following formula:

$N = k_L aV (C_o - C_L)$ (1)

C_o is basically the initial concentration of the oxygen in the gas and C_L is the equilibrium concentration in the liquid. Originally the film theory suggest**s** that there are two transfer coefficient involved in the gas to liquid mass transfer which is:

- Mass transfer coefficient of liquid, k_La
- Mass transfer coefficient of the gas,k_Ga

However the mass transfer coefficient of the gas is ignored in the calculation as the gas phase has a high diffusivities compare to the liquid phase.

2.31 Gas Bubbles Interfacial Area

The interested variable which is the gas liquid interfacial area a is will determine the k_La value. The value of a is affected by 2 parameters which is

- The gas hold
- Mean diameter of the bubbles ,D_b

The parameters like power consumption, gas hold-up, dispersion mixing intensity and volumetric mass transfer coefficient is crucial to design the stirred gas liquid contactor vessel (Moucha et al., 2003)**.**The following shows the equation for interfacial area,a. The interfacial are a, is defined by the gas-interfacial area (m^2) per unit liquid volume (m^3) which can be written as:

$$\boldsymbol{a = \frac{6}{Db} * \xi g} \qquad (2)$$

From the equation a new term ξ_g is introduced. The term ξ_g is basically the gas hold up which is the volume of bubbles per volume of liquid. The technique to measure the gas hold up will be further discuss in the measurement techniques in this literature review section. Based on the derivation of the equation 2.20 it can be shown the interfacial area is the function of the mean diameter of the bubbles and the gas hold up. The main of the project is to improve the interfacial which will determine the rate of mass transfer as the value of k_L is constant based on the equation 2.10. In order to increase the interfacial area, the value of the gas hold up should be increase. The value of the gas hold up itself is the indicator of the mass transfer between the gas and the liquid**.** Meanwhile the other contributing factor which is the mean diameter of the bubbles $D_{b,}$ should be decreased based on the derived equation 2.20 in order to increase the interfacial area and hence increase the mass transfer. For this purpose small and dispersed bubbles is desired and this is why the impeller blade is needed in order to stir the mixture and ensure the mixing of gas and liquid takes place in the contactor.

2.4 Measurement Techniques

2.41 Measurement of K_La

The used of right technique in the evaluation of k_La is important in order to ensure the accuracy of the data obtained in the experiment. In order to choose the technique to be used many factors should be considered which is not the only the accuracy of the technique but also the cost and accessibility of the equipment. To ensure the accuracy of the experimental data obtained in calculating the value of volumetric mass transfer coefficient the suitable technique must be applied in calculating the value of volumetric mass transfer coefficient. Basically There are two types of techniques in the measurement of the volumetric mass transfer coefficient kLa which are the steady state and dynamic technique. the absorbed gas component has to be constantly removed from the liquid phase in the steady state operation techniques .In order to maintain significant concentration difference of the absorbing agent between the gas and the liquid phase it is vital to ensure that the gas removal is fast enough and by using physical desorption or with the assist of chemical reaction, the absorbed gas component can be removed from the system (Baier, 2001).Besides that simulation work has also been done in order to evaluate the volumetric mass transfer coefficient k_La value. In the simulation study population balance model (PBM) was solved using quadrature method of moments (QMOM) in order to find the local bubble size distribution. The Higbie penetration theory and the surface renewal model were also used in the estimation of local volumetric mass transfer coefficient (Gimbun et al., 2009).

2.42 Measurement of the Bubbles Diameter, D_B

The measurement of the bubble diameter is necessary in order to find the interfacial area, a based on the equation 2.20. One of the techniques that can be used for the purpose is by taking of photograph of the bubbles profile. For this proposed experiment, the photo of the bubbles is taken outside of the gas liquid contactor using a camera. The photo will be analyzed in order to obtain the mean diameter of the bubbles.

Besides that, the particle image velocimetry (PIV) was also used in order to take the photograph of the gas-liquid dispersion (Chen and Fan, 1992). The measurement of the interfacial area is also done using light sheet and image analysis (Busciglio et al., 2010).

2.43 Measurement of Gas Hold Up, ξg.

The gas hold up is also one of the important parameter that determines the interfacial area for mass transfer. By measuring the increase in the liquid level before and after the gas is introduced into the vessel the overall gas hold-up can be easily measured. However for a low gas hold up in the gas liquid system this method is generally not accurate (Busciglio et al., 2010). Recently Particle image velocimetry (PIV) have been used in investigating the turbulence quantities and the flow field in a gas liquid system (Montante et al., 2007) and it also focused on the simultaneous measurement of gas and liquid flow-field quantities with the application of back lighting and macro lenses (Sommerfeld and Broder, 2009). Besides that a new experimental technique to measure the intercept of bubble sizes and its position in the contacting vessel was presented where the application of fluorescent liquid phase excited by a laser sheet was used. The bubbleswhich is intercepted by the laser sheet projected the “shadows” and the image processing algorithm is adopted for the automatic recognition of the “shadows” projected (Busciglio et al., 2010). In general there are many techniques recently used by the previous researches in determining the gas hold up, however each techniques and procedure used in the evaluation of the bubbles has its own advantages and disadvantages. For example the presence of the probe will affect the flow field in the gas liquid contacting vessel and longer experiment time is required to acquire the data distribution over the entire system. Other than that the coalescence behavior of the system and the dispersion properties is affected by the use of chemical in measuring the gas liquid interfacial area (Busciglio et al., 2010).

3. METHODOLOGY

3.1 Project Flow Chart

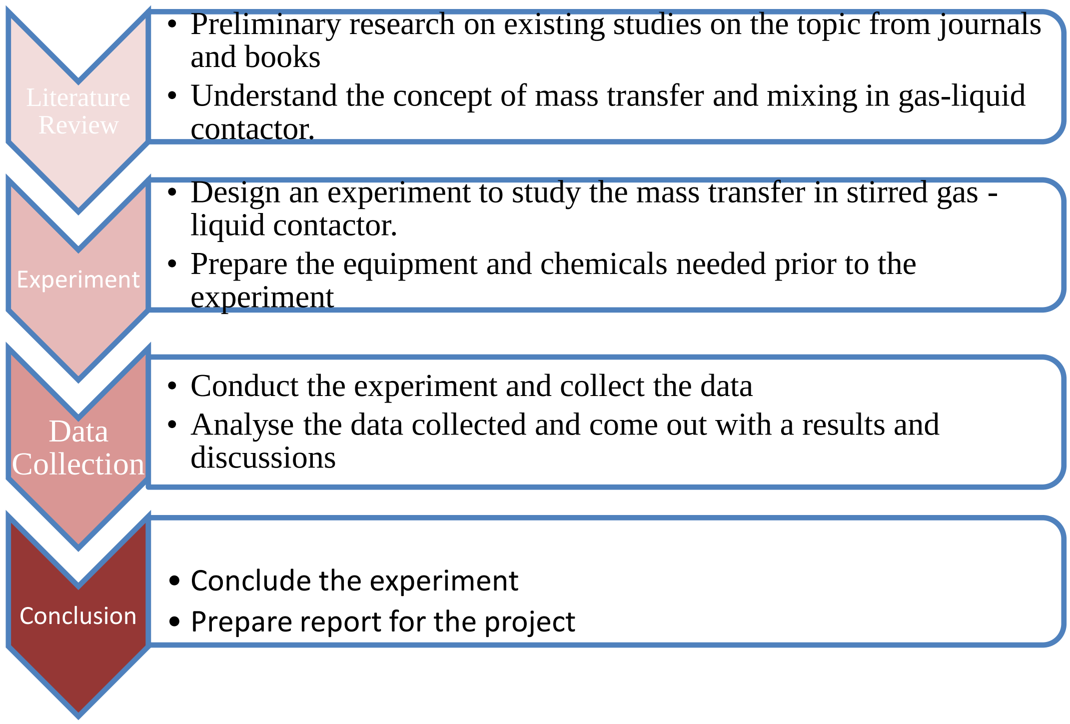

FIGURE 1. Project Flow Chart

3.2 Experimental Setup

The figure 1 below shows the proposed schematic diagram for experimental set up for this proposed study. The objective of the experiment for this experiment is to investigate the effect of impeller speed and power and the gas flow rate to the volumetric mass transfer coefficient will be studied. The setup of the experiment are as follows:

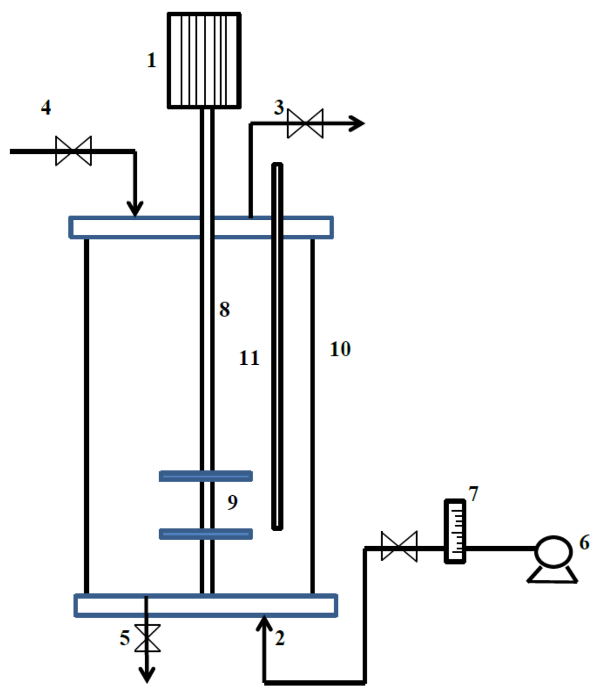

FIGURE 2. Experimental Setup

TABLE 1. Equipment Components

Number	Component
1	Variable motor
2	Inlet air line
3	Outlet air line
4	Inlet Liquid
5	Outlet Liquid
6	Compressor
7	Flow meter
8	Shaft
9	Impeller
10	Tank body
11	DO electrode

3.3 Gantt Chart and Key Milestone

Activities	Week														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Project Work Continues															
Submission of Progress Report															
Project Work Continues															
Pre Sedex															
Submission of Draft Final Report															
Submission of Dissertation(Soft Bound)															
Submission of Technical Paper															
Viva															
Submission of Dissertation(Hard Bound)															

Process

Suggested milestone

3.4 Experiment Methodology

3.41 Tools and equipment

For the mass transfer in stirred gas liquid contactor, the essential part of the equipment is the contacting vessel. In this proposed experiment. Common shafts will be used for the vessels. For the laboratory scaled vessel the single Rushton turbine impeller will be used where inner diameter T=28.4 cm and the diameter of the impeller blade is D is 6 cm.

A compressor is equipped in order to enable the air flow into the vessel through the gas sparger and a gas flow rate controller will be used in order to regulate the flow rate of the gas. Besides that the flow rate of the air can be read from the air flow meter. Nitrogen also can be used in the proposed experiment for the Oxygen purging purpose (Kapic et al., 2006). DO meter will be used to check the dissolved oxygen concentration in liquid.

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3.42 Material

The lists of material needed in this process are air(oxygen) and water.

3.43 Designed experiment

The experiment is designed by finding the critical impeller speed which will further discussed in result and discussion for every flow rate based on the following table.

TABLE 2. Designed Experiment

Gas Flow Rate ,Q_g(Liter/min)	180 rpm	200 rpm	220 rpm	280 rpm	300 rpm
5	Run 1	Run 2	Run 3	Run 4	Run 5
10	Run 6	Run 7	Run 8	Run 9	Run 10
15	Run 11	Run 12	Run 13	Run 14	Run 15
20	No Run	Run 16	Run 17	Run 18	Run 19
25	No Run	No run	Run 20	Run 21	Run 22

3.44 Proposed Experimental Procedure

The experiment is planned to be conducted in batch mode for about 15- 40 minutes depending on the time where the equilibrium mass transfer is achieved(shown by constant dissolved oxygen meter reading) The experiment will be divided into 22 run based on the Table 2.

<u>Experiment Procedures</u>

1) Turn on the compressor and start the air flow rate into the vessel at the flow of 5 L/minute.

2) The impeller speed is adjusted at the speed of 180 rpm (Run 1)

5) The reading of the dissolved Oxygen meter is taken for every 1 minute until 15 minutes (If the equilibrium Concentration is not achieved in 15 minutes the experiment should be continued until constant Oxygen concentration is achieved.)

6) The experiment is repeated for every run from run to 2 to run 22 with the flowrate and impeller speed to be used is specified in the Table 2.

7) The graph of dissolved oxygen concentration as the function of time is plotted for each of the run to find k_La valus.

4. RESULT AND DISCUSSION

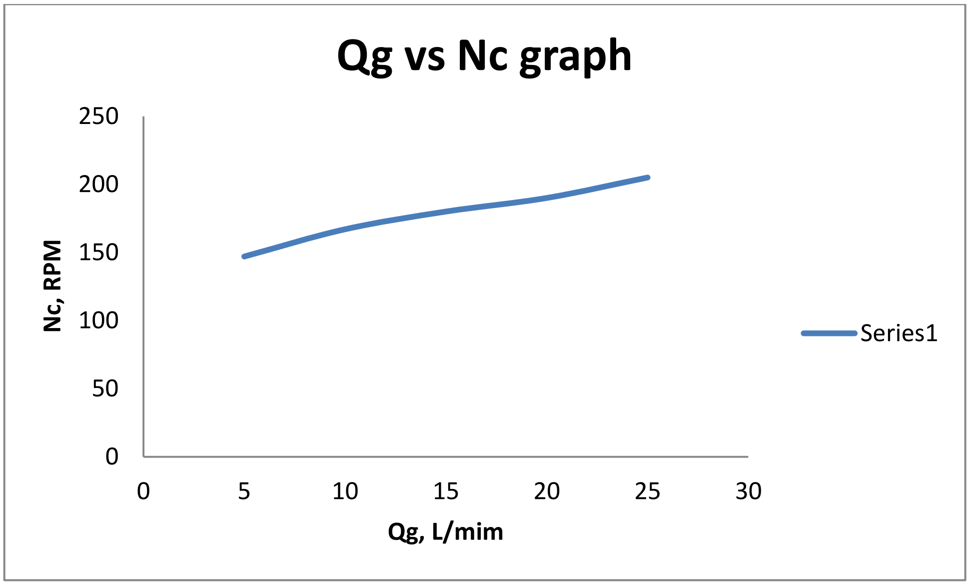

FIGURE 3. Graph of Gas Flow Rate Q_g vs Critical Impeller Speed

Before running the experiment the critical impeller speed, N_C is the parameter that need to be obtained. The graph in Figure 3 shows the correlation between the gas flow rate and the impeller speed. Critical impeller speed in this context refer to the minimum speed in which the Rushton impeller used in the experiment would be able to to break the air bubbles in order to induce mass transfer from oxygen to water. In this project the equation for the minimum impeller speed for system is manage to be obtained by the following equation 3.(The data of the plot is provided in the appendix)

$N_C = 105.97.19Q_g^{0.1991}$ (3)

Based on the equation the critical impeller speed is in the exponential function of the gas flow rate and from this equation the experiment is designed by finding the suitable impeller speed to be used for the vessel to ensure the mass transfer is taking place. For instance , the critical impeller speed for 15 Liter/ min air flow rate is 180 rpm. Hence the impeller speed used for 15 L/min is 180 rpm and more where 180, 200,220 and 300 rpm have been used in order to break the bubble. The same methodology is used in designing the impeller speed to be used for other flow rate of the gas. In addition, inside the stirred tank there are 2 main mechanism taking place which is the impeller speed and the air flow rate coming into the tank. If the air flow rate is stronger than the impeller speed used in this system the flooding phenomena will happen. The flooding phenomena refer to the condition in which the speed and power provided to the impeller is not sufficient to break the air bubbles causing the air bubble to rise up without any bubble breakage. Hence mass transfer operation will not happen and flooding phenomena should be avoided by finding the critical impeller speed N_C which is the basis of designing the experiment. The increase in the dissolved oxygen reading shown by DO meter is noted where it indicate the mass transfer operation is taking place in this experiment. The following table shows the gas flow rate and the respective critical impeller speed which is used in designing this experiment.

TABLE 3. Critical Impeller Speeds

Gas Flow Rate	Critical Impeller Speed
5	147.5
10	166
15	180
20	190
25	205

In defining the critical impeller speed two concepts should be acknowledged which is the gas flow overpower and impeller speed overpower. The gas flow overpower is the condition that must be avoided in the operation of gas liquid mass transfer as in this condition the impeller is overpowered by the gas flow and the bubbles is not dispersed by the impeller. In the other hand the impeller speed overpower is desired in order to break the bubbles and transfer the oxygen into the water.

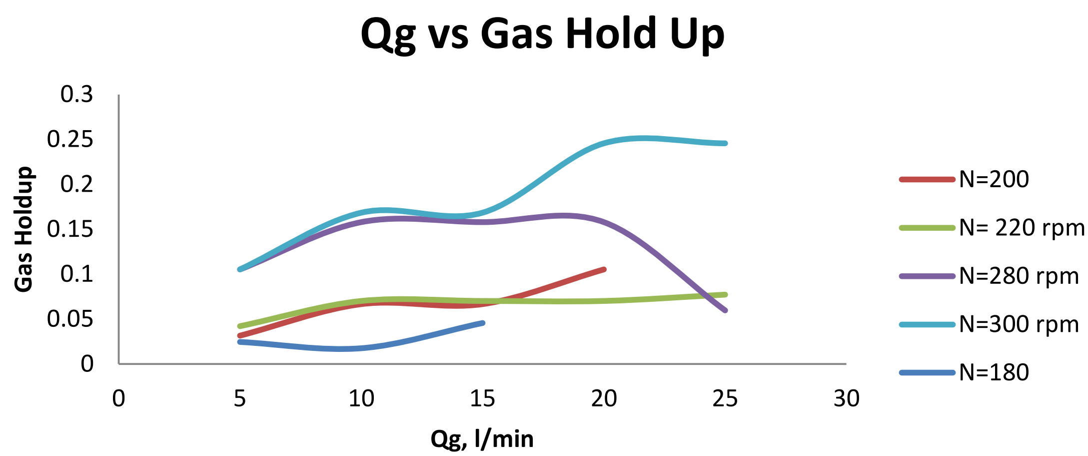

FIGURE 4. Graph of Gas Flow Rate, Q_g vs Gas Hold Up,ξ_g

After the critical impeller speed is obtained, the experiment is done based on the procedure outlined and the graph of the gas flow rate vs the gas hold up is obtained based on Figure 4 where it is shown that for the impeller speed of 300 rpm will give the highest amount of gas hold up in the vessel compare to other impeller speed and the equation obtained for the gas flow rate in the function of impeller speed for 300 rpm is $\xi_g=0.0958e^{0.0414Qg}$. Meanwhile for the impeller speed of 280 rpm the value for gas hold up ξ_g obtained increase from 5 L/min to 10 and 15 L/min before the value drop for the flow rate of 20 and 25 Liter/min. The result obtained for 280 rpm impeller speed is suspected to an error as the pattern of the gas hold up increment is different from other impeller speed where for the impeller speed of 180 to 220 rpm the gas hold up increase with the increment of the air flow rate used in the experiment. Meanwhile the result also show that the lowest impeller speed used which is 180 rpm will induce the least height gas hold up. The explanation for the result is that lower impeller speed will have lower power to break and disperse the bubble inside the tank. Hence, the bubbles are not well dispersed resulting to the lower rate of mass transfer of the oxygen to the water. This is shown by the low value of gas hold up obtained. The equations obtained for the gas hold up in the function of the gas flow rate for each impeller speed are based on the following table.

TABLE 4.	Gas Hold Up Correlation

Impelller speed	Correlation
180 rpm	$\xi_g=0.0145e^{0.0169Qg}$
200 rpm	$\xi_g=0.0251e^{0.0722Qg}$
220rpm	$\xi_g=0.0448e^{0.0242Qg}$
280 rpm	$\xi_g=0.16858e^{-0.023Qg}$
300 rpm	$\xi_g=0.0958e^{0.0414Qg}$

From the correlation obtained gas hold up can be predicted for the any of gas flow rate used in this experiment at the defined impeller speed. The correlation obtained provides a good approach in order to estimate the gas hold up and designing the future experiment in a more systematic way. The following figure shows image of the stirred vessel where the gas hold up at the function of gas flow rate is measured at the tested impeller speed.

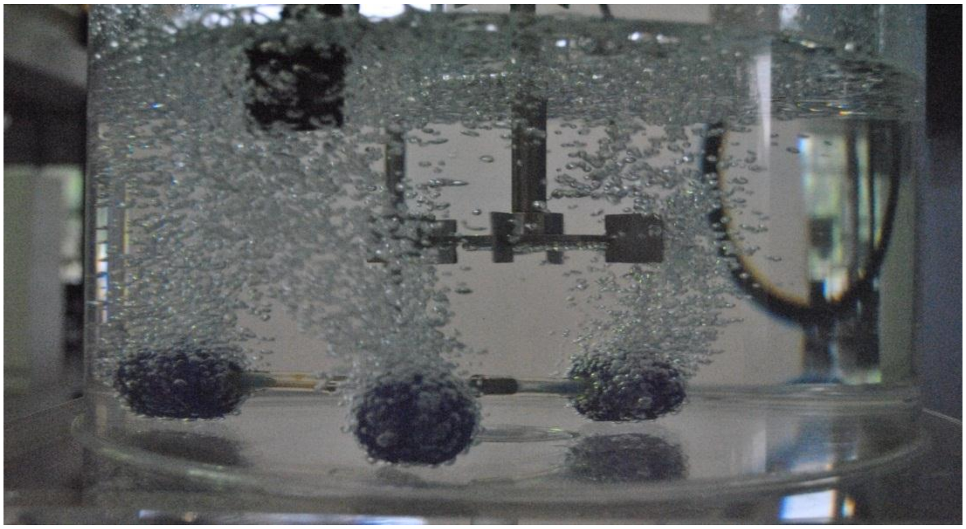

FIGURE 5.	Image of Stirred Vessel

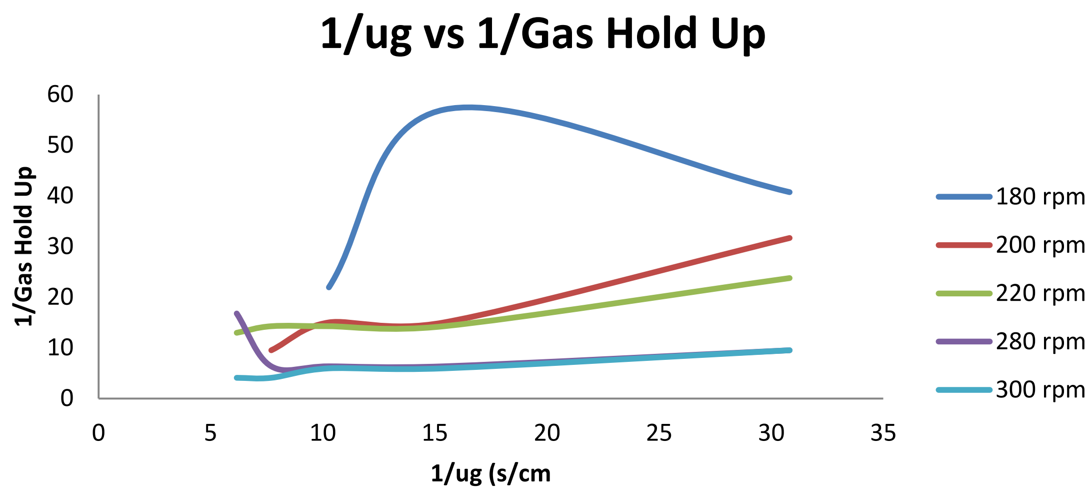

FIGURE 6. Graph of 1/ug (s/cm) vs 1/ gas hold up

The next analysis done is this project is the analysis of the graph of $1/u_g$ vs $1/\xi_g$ where from the objective of this analysis is to find the slope of the graph.The slope of the graph is obtained from the slope based on the equation proposed by Sable(1993):

$$\frac{ug}{\xi g} = 1 + \frac{ubr + ucr - C1ND}{ug} \qquad (4)$$

Where u_g=velocity of the gas(cm/s)

ubr= buble velocity (cm/s)

ND=impeller tip speed

C1=Constant.

From the slope of the graph the value of ubr+ucr can be obtained where ubr+ucr is the slope of the graph based on the figure 6 where the slope for the 180 rpm impeller speed is 1.7804 cm/s, 200 rpm graph is 1.0133,220 is 0.8755, 280 rpm is 0.3864, and 300 rpm is 0.3163.

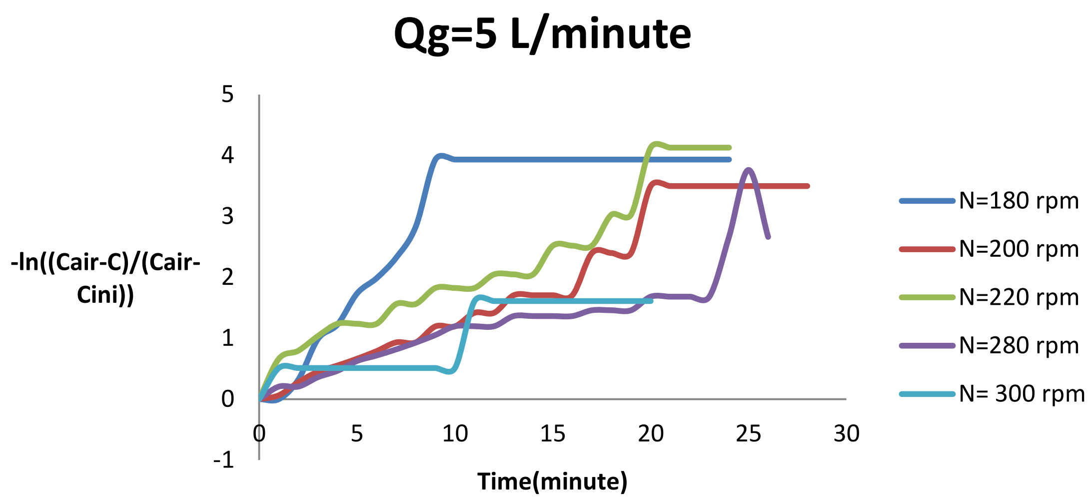

FIGURE 7. Graph of time vs -LN((Cair-C)/(Cair-Cin)) for 5 L/minute

TABLE 5. k_La values for Q_g= 5 Liter/minute

Impeller speed (rpm)	k_La (1/minute)
180	0.2257
200	0.1381
220	0.1773
280	0.0972
300	0.0967

In order to find k_La value for Q_g= 5 Liter/minute , the graph based on figure 7 is plotted where the slope shows the value of k_La .Cair refer to the maximum air concentration, C refer to the instantaneous concentration and Cin refer to initial concentration of oxygen in the air. To verify this the unit of the slope is the same as unit of k_La which is 1/minute or it can be converted to 1/ second. slope obtained is tabulated in Table 5.Based on the table the value of k_La is highest for impeller speed of 180 rpm, however error is suspected as the value of k_La should be higher by using higher impeller speed.. As the impeller speed increase from 200 to 220 rpm, the values of k_La increase while it begin to decrease at the speed of 280 and 300 rpm.

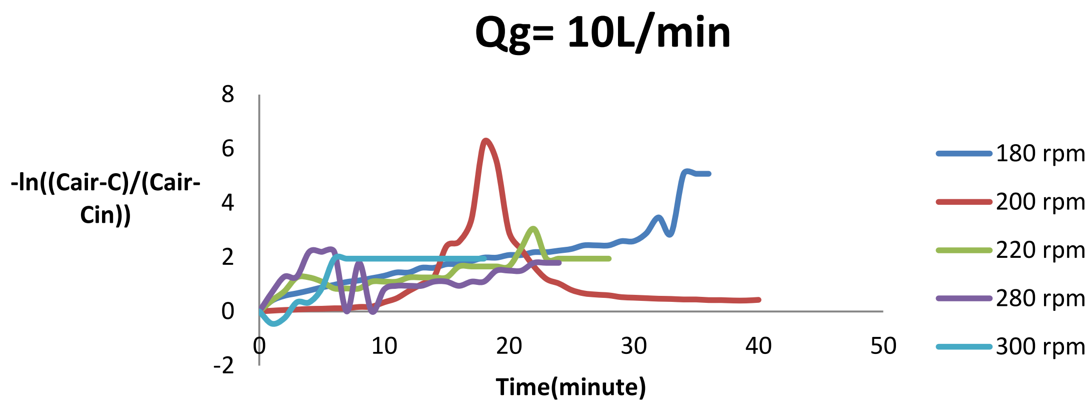

FIGURE 8. Graph of time vs -LN((Cair-C)/(Cair-Cin)) for 10 L/minute

Table 6. k_La values for Q_g= 10 Liter/minute

Speed(rpm)	180	200	220	280	300
k_La(1/minute)	0.109	0.0387	0.905	0.0808	0.1466

Figure 8 shows the graph plotted between time vs - ln ((Cair-C)/(Cair-Cin))like the previous graph. From the calculation obtained based on Table 6 the value of the slope, k_La is obtained. Based on the result 80 rpm impeller speed shows the highest k_La value where error is also suspected as the value of other higher impeller speed should give the higher value of k_La. However the pattern is increasing for the value of k_La from 200 rpm to 300 rpm impeller speed from 0.0387 to 0.1466 per minute. This shows a reliable result where increasing impeller speed will give a higher value of mass transfer as based on the literature, the higher speed will have more power to break and disperse the bubbles around the defined volume of the vessel.

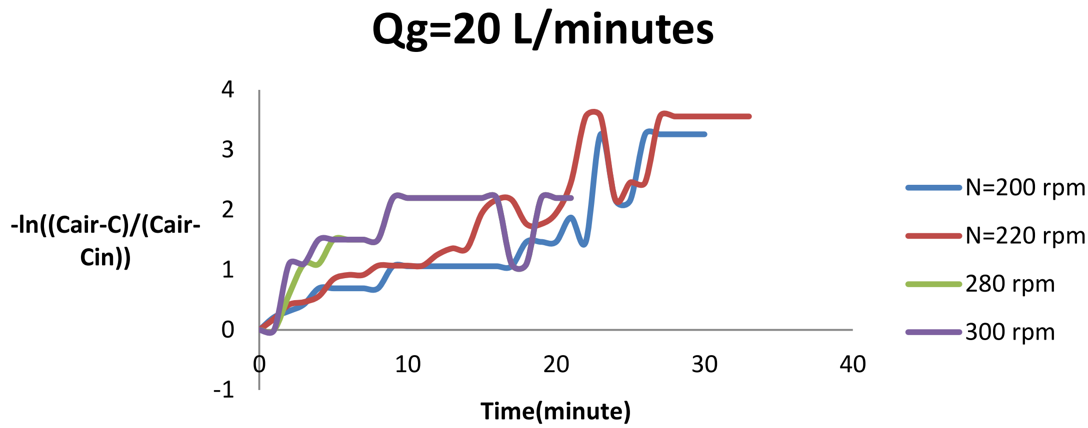

FIGURE 9. Graph of time vs -Ln((Cair-C)/(Cair-Cin)) for 20 L/minute

Table 7. k_La value for Q_g= 20 Liter/ minute

Speed(rpm)	180	200	220	280	300
k_La(1/minute)	-	0.0993	0.116	0.1323	0.1331

Figure 9 the Graph of time vs -Ln((Cair-C)/(Cair-Cin)) for 20 L/minute where the value of the slope which is k_La is tabulated for the impeller speed in Table 7. The value for 180 rpm is not tabulated as the value of critical speed N_c for 20 Liter /minute is more than 180 rpm. Hence 180 rpm speed cannot disperse the bubble with this flow rate.From the result obtained in the table it is shown that the result is reliable as the increase in the impeller speed give the higher value of k_La from 200 rpm to 300 rpm. For the value of 280 rpm to 300 rpm the value of k_La is quite close and based on the mass transfer theory for the gas-liquid contacting vessel there is some extent where the value of k_La is not increasing with the increase of impeller speed. Hence if more run is conducted, the value offset value for the impeller speed can be obtained. In this experiment, the result for k_La value for Q_g=15 Liter/minute and 25 L/minute is not presented as the result shows many error and cannot be analyzed.

5. CONCLUSION AND RECCOMENDATION

As a conclusion, this project is important as it deals with the improvement of the mass transfer rate which can bring a significant impact in the operation of the gas liquid stirred tank. From this experiment, the correlation for the critical gas flow rate vs critical impeller speed manage to be derived for the system of 28.5 cm tank diameter(T) and 6 cm impeller diameter which is shown by equation 3.

$N_C = 105.97.19Q_g^{0.1991}$ (3)

By obtaining the correlation for the critical impeller speed, the future framework can be designed for this tank in order to run more experiment to increase the effectiveness of the gas liquid mass transfer for this vessel. Besides that, the correlation between the gas hold up and gas flow rate at the function of impeller speed also managed to be derived for the vessel based on the table.

TABLE 4. Gas Hold Up and Gas Flow Rate Correlation

Impelller speed	Correlation
180 rpm	ξ_g=0.0145$e^{0.0169Qg}$
200 rpm	ξ_g=0.0251$e^{0.0722Qg}$
220rpm	ξ_g=0.0448$e^{0.0242Qg}$
280 rpm	ξ_g=0.16858$e^{-0.023Qg}$
300 rpm	ξ_g=0.0958$e^{0.0414Qg}$

Based on the correlation obtained the value for the gas hold up can be predicted for any gas flow rate used at the defined impeller speed. Hence by obtaining this correlation, it will also provide a good approach in estimating the gas hold up for the planned future experiment and the method of estimating the parameters to be used for the experiment will be more systematic.

Besides that it can also be concluded that for the gas flow rate Q_g of 10 liter/ minute increasing the impeller speed from 200 rpm to 300 rpm will give a better k_La value while for gas flow rate Q_g of 20 liter/ minute the same pattern is observed 200 rpm to 300rpm. Other than that the distribution of k_La values for the Q_g of 15 liter/ minute and 25 liter/ minute is not able to be presented as there is some error in the result obtained especially the reading of the dissolved oxygen per time. Some of the recommendation for this is to always check and calibrate the dissolved oxygen meter so that the reading shown will be reliable for the analysis of the experiment. The reading obtained from dissolved oxygen meter is important because it will affect the calculation of k_La values. Besides that, the other recommendation for this project is to provide an equipment to measure the gas hold up. This is because the gas hold up is measured by recording the height of the aerated liquid while the liquid level is keep fluctuating. This condition will somehow contribute error to the experiment and an equipment should be installed for the purpose of measuring gas hold up.

Overall, it can be concluded that this work should be continued in order to find the best correlation of the involved parameters in order to achieve the highest value of k_La.Besides that, the application of the stirred tank operation parameters is integrated with the knowledge of gas liquid mixing. The project is within capability of a final year student to be executed with the help and guidance. The time frame is also feasible and the project can be completed within the time allocated.

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7. APPENDICES

Appendix 1. Gas Hold Up Data

Gas Flow Rate Q_g(L/min)	180 rpm	200 rpm	220 rpm	280 rpm	300 rpm
5	0.0245614	0.03157895	0.04210526	0.10526316	0.10526316
10	0.01754386	0.06666667	0.07017544	0.15789474	0.16842105
15	0.04561404	0.06666667	0.07017544	0.15789474	0.16842105
20	No run	0.10526316	0.07017544	0.15789474	0.24561404
25	No run	No run	0.07719298	0.05964912	0.24561404

Appendix 2. Slope Data for 1/ug vs 1 / Gas Hold Up Data.

Impeller Speed, N(rpm)	Slope(cm/s)
180	1.7804
200	1.013
220	0.8755
280	0.3864
300	0.3103

Appendix 3. Critical Impeller Speed for Various Flowrate

Impeller Speed, N(rpm)	Slope(cm/s)
180	147
200	167
220	180
280	190
300	205

Appendix 4. Dissolved Oxygen Reading vs Time for Qg= 5 L/min, N=180 rpm

Time(minute)	Dissolved Oxygen (mg/L) for 180 rpm	-ln((Cair-C)/(Cair-Cin))
0	8.09	0
1	8.09	0
2	8.23	0.32090772
3	8.41	0.987386654
4	8.45	1.223775432
5	8.51	1.734601055
6	8.53	1.985915484
7	8.55	2.32238772
8	8.57	2.833213344
9	8.59	3.931825633
10	8.59	3.931825633
11	8.59	3.931825633
12	8.59	3.931825633
13	8.59	3.931825633
14	8.59	3.931825633
15	8.59	3.931825633
16	8.59	3.931825633
17	8.59	3.931825633
18	8.59	3.931825633
19	8.59	3.931825633
20	8.59	3.931825633
21	8.59	3.931825633
22	8.59	3.931825633
23	8.59	3.931825633
24	8.59	3.931825633

Appendix 5. Dissolved Oxygen Reading vs Time for Qg= 5 L/min, N=200 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.24	0
1	8.26	0.062520357
2	8.32	0.277631737
3	8.36	0.451985124
4	8.38	0.552068582
5	8.4	0.663294217
6	8.42	0.78845736
7	8.44	0.931558204
8	8.44	0.931558204
9	8.47	1.193922468
10	8.47	1.193922468
11	8.49	1.41706602
12	8.49	1.41706602
13	8.51	1.704748092
14	8.51	1.704748092
15	8.51	1.704748092
16	8.51	1.704748092
17	8.54	2.397895273
18	8.54	2.397895273
19	8.54	2.397895273
20	8.56	3.496507561
21	8.56	3.496507561
22	8.56	3.496507561
23	8.56	3.496507561
24	8.56	3.496507561
25	8.56	3.496507561
26	8.56	3.496507561
27	8.56	3.496507561
28	8.56	3.496507561

Appendix 6. Dissolved Oxygen Reading vs Time for Qg= 5 L/min, N=220 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	7.82	0
1	8.12	0.661398482
2	8.16	0.794929875
3	8.22	1.036091932
4	8.26	1.236762627
5	8.26	1.236762627
6	8.26	1.236762627
7	8.31	1.562185028
8	8.31	1.562185028
9	8.34	1.824549292
10	8.34	1.824549292
11	8.34	1.824549292
12	8.36	2.047692843
13	8.36	2.047692843
14	8.36	2.047692843
15	8.39	2.517696473
16	8.39	2.517696473
17	8.39	2.517696473
18	8.41	3.028522096
19	8.41	3.028522096
20	8.43	4.127134385
21	8.43	4.127134385
22	8.43	4.127134385
23	8.43	4.127134385
24	8.43	4.127134385

Appendix 7. Dissolved Oxygen Reading vs Time for Qg= 5 L/min, N=280 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.27	0
1	8.35	0.205852054
2	8.35	0.205852054
3	8.4	0.360002734
4	8.43	0.46536325
5	8.47	0.6257059
6	8.49	0.716677678
7	8.51	0.816761137
8	8.53	0.927986772
9	8.55	1.053149915
10	8.57	1.196250758
11	8.57	1.196250758
12	8.57	1.196250758
13	8.59	1.363304843
14	8.59	1.363304843
15	8.59	1.363304843
16	8.59	1.363304843
17	8.6	1.458615023
18	8.6	1.458615023
19	8.6	1.458615023
20	8.62	1.681758574
21	8.62	1.681758574
22	8.62	1.681758574
23	8.62	1.681758574
24	8.67	2.662587827
25	8.69	3.761200116
26	8.67	2.662587827

Appendix 8. Dissolved Oxygen Reading vs Time for Qg= 5 L/min, N=300 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.57	0
1	8.59	0.510826
2	8.59	0.510826
3	8.59	0.510826
4	8.59	0.510826
5	8.59	0.510826
6	8.59	0.510826
7	8.59	0.510826
8	8.59	0.510826
9	8.59	0.510826
10	8.59	0.510826
11	8.61	1.609438
12	8.61	1.609438
13	8.61	1.609438
14	8.61	1.609438
15	8.61	1.609438
16	8.61	1.609438
17	8.61	1.609438
18	8.61	1.609438
19	8.61	1.609438
20	8.61	1.609438

Appendix 9 . Dissolved Oxygen Reading vs Time for Qg= 10 L/min, N=180 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.09	0
1	8.61	0.393042588
2	8.79	0.575364145
3	8.87	0.668454568
4	8.95	0.771108722
5	9.03	0.885519073
6	9.09	0.980829253
7	9.15	1.086189769
8	9.18	1.143348183
9	9.22	1.225026214
10	9.26	1.3139737
11	9.31	1.437587656
12	9.31	1.437587656
13	9.37	1.609437912
14	9.37	1.609437912
15	9.41	1.742969305
16	9.41	1.742969305
17	9.44	1.85629799
18	9.47	1.984131362
19	9.47	1.984131362
20	9.49	2.079441542
21	9.49	2.079441542
22	9.51	2.184802057
23	9.51	2.184802057
24	9.52	2.241960471
25	9.53	2.302585093
26	9.55	2.436116486
27	9.55	2.436116486
28	9.55	2.436116486
29	9.57	2.590267165
30	9.57	2.590267165
31	9.6	2.877949238
32	9.64	3.465735903
33	9.6	2.877949238
34	9.68	5.075173815
35	9.68	5.075173815
36		

Appendix 10 . Dissolved Oxygen Reading vs Time for Qg= 10 L/min, N=200 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	9.14	0
1	9.28	0.027834799
2	9.4	0.052325819
3	9.48	0.068992871
4	9.59	0.09237332
5	9.62	0.098845835
6	9.7	0.116313528
7	9.72	0.120728546
8	9.92	0.165985137
9	9.97	0.177626712
10	10.6	0.337256858
11	11.1	0.48501774
12	11.85	0.757947174
13	12.37	1.003302109
14	12.81	1.271566095
15	13.78	2.405769329
16	13.85	2.57084908
17	14.07	3.401197382
18	14.23	6.234410726
19	14.22	5.541263545
20	13.97	2.93857386
21	13.72	2.283167007
22	13.27	1.659699747
23	12.7	1.197458123
24	12.42	1.030404039
25	11.93	0.791993015
26	11.62	0.666066222
27	11.5	0.621282619
28	11.42	0.592503655
29	11.23	0.527300461
30	11.17	0.507562978
31	11.11	0.488207535
32	11.05	0.469219623
33	11.02	0.45985918
34	10.96	0.441397117
35	10.96	0.441397117
36	10.88	0.417299566

Appendix 11 . Dissolved Oxygen Reading vs Time for Qg= 10 L/min, N=220 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	10.29	0
1	10.36	0.405465108
2	10.4	0.741937345
3	10.44	1.252762968
4	10.44	1.252762968
5	10.43	1.098612289
6	10.41	0.84729786
7	10.41	0.84729786
8	10.41	0.84729786
9	10.43	1.098612289
10	10.43	1.098612289
11	10.43	1.098612289
12	10.44	1.252762968
13	10.44	1.252762968
14	10.44	1.252762968
15	10.44	1.252762968
16	10.46	1.658228077
17	10.46	1.658228077
18	10.46	1.658228077
19	10.46	1.658228077
20	10.46	1.658228077
21	10.48	2.351375257
22	10.49	3.044522438
23	10.47	1.945910149
24	10.47	1.945910149
25	10.47	1.945910149
26	10.47	1.945910149
27	10.47	1.945910149
28	10.47	1.945910149

Appendix 12 . Dissolved Oxygen Reading vs Time for Qg= 10 L/min, N=280 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	10.34	0
1	10.43	0.693147181
2	10.47	1.280933845
3	10.47	1.280933845
4	10.5	2.197224577
5	10.5	2.197224577
6	10.5	2.197224577
7	10.52	-
8	10.49	1.791759469
9	10.52	-
10	10.44	0.810930216
11	10.45	0.944461609
12	10.45	0.944461609
13	10.45	0.944461609
14	10.46	1.098612289
15	10.46	1.098612289
16	10.45	0.944461609
17	10.46	1.098612289
18	10.46	1.098612289
19	10.48	1.504077397
20	10.48	1.504077397
21	10.48	1.504077397
22	10.49	1.791759469
23	10.49	1.791759469
24	10.49	1.791759469

Appendix 13 . Dissolved Oxygen Reading vs Time for Qg= 10 L/min, N=300 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.36	0
1	8.32	-0.451985124
2	8.34	-0.251314428
3	8.38	0.336472237
4	8.38	0.336472237
5	8.4	0.84729786
6	8.42	1.945910149
7	8.42	1.945910149
8	8.42	1.945910149
9	8.42	1.945910149
10	8.42	1.945910149
11	8.42	1.945910149
12	8.42	1.945910149
13	8.42	1.945910149
14	8.42	1.945910149
15	8.42	1.945910149
16	8.42	1.945910149
17	8.42	1.945910149
18	8.42	1.945910149

Appendix 14 . Dissolved Oxygen Reading vs Time for Qg= 15 L/min, N=180 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	9.63	0
1	9.69	0.150282203
2	9.71	0.205852054
3	9.74	0.295464213
4	9.78	0.428995606
5	9.84	0.670157662
6	9.87	0.816761137
7	9.89	0.927986772
8	9.87	0.816761137
9	9.9	0.988611393
10	9.94	1.276293466
11	9.92	1.122142786
12	9.98	1.681758574
13	9.98	1.681758574
14	9.95	1.363304843
15	9.97	1.563975538
16	9.98	1.681758574
17	9.96	1.458615023
18	9.99	1.815289967
19	9.97	1.563975538
20	9.99	1.815289967
21	9.99	1.815289967
22	9.99	1.815289967
23	9.99	1.815289967
24	9.99	1.815289967
25	10.02	2.374905755
26	10.02	2.374905755
27	10.02	2.374905755
28	10.02	2.374905755
29	10.04	3.068052935
30	10.04	3.068052935

Appendix 15 . Dissolved Oxygen Reading vs Time for Qg= 15 L/min, N=200 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	7.94	0
1	9.5	1.269023489
2	9.61	1.467874348
3	9.7	1.666325287
4	9.78	1.883389792
5	9.82	2.012601524
6	9.9	2.335374916
7	9.91	2.38416508
8	9.93	2.489525596
9	9.97	2.740840024
10	9.97	2.740840024
11	9.98	2.814947996
12	9.98	2.814947996
13	9.98	2.814947996
14	9.98	2.814947996
15	10.01	3.077312261
16	10.04	3.433987204
17	10.04	3.433987204
18	10.04	3.433987204
19	10.05	3.588137884
20	10.05	3.588137884
21	10.04	3.433987204
22	10.04	3.433987204
23	10.04	3.433987204
24	10.1	5.379897354
25	10.09	4.686750173
26	10.09	4.686750173
27	10.07	3.993602992
28	10.11	0
29	10.09	4.686750173
30	10.09	4.686750173
31	10.12	0

Appendix 16 . Dissolved Oxygen Reading vs Time for Qg= 15 L/min, N=220 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	9.63	0
1	9.79	0.416160397
2	9.87	0.714653386
3	9.91	0.905708623
4	9.96	1.211090272
5	9.97	1.285198244
6	9.98	1.365240952
7	10.02	1.77070606
8	10	1.547562509
9	10.09	3.850147602
10	10.06	2.463853241
11	10.05	2.240709689
12	10.05	2.240709689
13	10.05	2.240709689
14	10.07	2.751535313
15	10.06	2.463853241
16	10.09	3.850147602
17	10.09	3.850147602
18	10.07	2.751535313
19	10.07	2.751535313
20	10.08	3.157000421
21	10.09	3.850147602
22	10.05	2.240709689
23	10.05	2.240709689
24	10.05	2.240709689
25	10.05	2.240709689
26	10.07	2.751535313
27	10.08	3.157000421
28	10.08	3.157000421
29	10.06	2.463853241
30	10.08	3.157000421

Appendix 17 . Dissolved Oxygen Reading vs Time for Qg= 15 L/min, N=280 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.39	0
1	8.69	0.202026628
2	9.77	1.84176989
3	9.97	3.308106959
4	9.97	3.308106959
5	10.01	4.406719247
6	10.02	5.099866428
7	10.02	5.099866428
8	9.82	2.05534399
9	9.73	1.698669046
10	9.7	1.603358866
11	9.64	1.436304782
12	9.75	1.767661918
13	9.62	1.386294361
14	9.58	1.293203938
15	9.56	1.249718826
16	9.55	1.228665417
17	9.53	1.187843422
18	9.51	1.148622709
19	9.49	1.110882381
20	9.49	1.110882381
21	9.49	1.110882381
22	9.49	1.110882381
23	9.47	1.074514737
24	9.47	1.074514737
25	9.47	1.074514737
26	9.46	1.05681516
27	9.46	1.05681516
28	9.47	1.074514737
29	9.46	1.05681516
30	9.48	1.092533243
31	9.48	1.092533243
32	9.47	1.074514737
33	9.47	1.074514737
34	9.47	1.074514737

Appendix 18 . Dissolved Oxygen Reading vs Time for Qg= 15 L/min, N=300 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.28	0
1	8.3	0.336472237
2	8.34	1.945910149
3	8.34	1.945910149
4	8.32	0.84729786
5	8.32	0.84729786
6	8.32	0.84729786
7	8.34	1.945910149
8	8.34	1.945910149
9	8.34	1.945910149
10	8.34	1.945910149
11	8.34	1.945910149
12	8.34	1.945910149
13	8.34	1.945910149
14	8.34	1.945910149
15	8.34	1.945910149
16	8.34	1.945910149
17	8.34	1.945910149
18	8.34	1.945910149

Appendix 20 . Dissolved Oxygen Reading vs Time for Qg= 20 L/min, N=200 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.28	0
1	8.33	0.2135741
2	8.35	0.313657559
3	8.37	0.424883194
4	8.41	0.693147181
5	8.41	0.693147181
6	8.41	0.693147181
7	8.41	0.693147181
8	8.41	0.693147181
9	8.45	1.060871961
10	8.45	1.060871961
11	8.45	1.060871961
12	8.45	1.060871961
13	8.45	1.060871961
14	8.45	1.060871961
15	8.45	1.060871961
16	8.45	1.060871961
17	8.45	1.060871961
18	8.48	1.466337069
19	8.48	1.466337069
20	8.48	1.466337069
21	8.5	1.871802177
22	8.48	1.466337069
23	8.53	3.258096538
24	8.51	2.159484249
25	8.51	2.159484249
26	8.53	3.258096538
27	8.53	3.258096538
28	8.53	3.258096538
29	8.53	3.258096538
30	8.53	3.258096538

Appendix 19 . Dissolved Oxygen Reading vs Time for Qg= 20 L/min, N=200 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.28	0
1	8.33	0.2135741
2	8.35	0.313657559
3	8.37	0.424883194
4	8.41	0.693147181
5	8.41	0.693147181
6	8.41	0.693147181
7	8.41	0.693147181
8	8.41	0.693147181
9	8.45	1.060871961
10	8.45	1.060871961
11	8.45	1.060871961
12	8.45	1.060871961
13	8.45	1.060871961
14	8.45	1.060871961
15	8.45	1.060871961
16	8.45	1.060871961
17	8.45	1.060871961
18	8.48	1.466337069
19	8.48	1.466337069
20	8.48	1.466337069
21	8.5	1.871802177
22	8.48	1.466337069
23	8.53	3.258096538
24	8.51	2.159484249
25	8.51	2.159484249
26	8.53	3.258096538
27	8.53	3.258096538
28	8.53	3.258096538
29	8.53	3.258096538
30	8.53	3.258096538

Appendix 20 . Dissolved Oxygen Reading vs Time for Qg= 20 L/min, N=220 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	9.83	0
1	9.89	0.188052232
2	9.95	0.419853846
3	9.96	0.464305608
4	9.98	0.559615788
5	10.03	0.84729786
6	10.04	0.916290732
7	10.04	0.916290732
8	10.06	1.070441412
9	10.06	1.070441412
10	10.06	1.070441412
11	10.06	1.070441412
12	10.08	1.252762968
13	10.09	1.358123484
14	10.09	1.358123484
15	10.13	1.945910149
16	10.14	2.1690537
17	10.14	2.1690537
18	10.12	1.763588592
19	10.12	1.763588592
20	10.13	1.945910149
21	10.15	2.456735773
22	10.17	3.555348061
23	10.17	3.555348061
24	10.14	2.1690537
25	10.15	2.456735773
26	10.15	2.456735773
27	10.17	3.555348061
28	10.17	3.555348061
29	10.17	3.555348061
30	10.17	3.555348061
31	10.17	3.555348061
32	10.17	3.555348061
33	10.17	3.555348061

Appendix 21 . Dissolved Oxygen Reading vs Time for Qg= 20 L/min, N=280 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.47	0
1	8.47	0
2	8.51	0.587787
3	8.53	1.098612
4	8.53	1.098612
5	8.54	1.504077
6	8.54	1.504077
7	8.54	1.504077
8	8.54	1.504077
9	8.55	2.197225
10	8.55	2.197225
11	8.55	2.197225
12	8.55	2.197225
13	8.55	2.197225
14	8.55	2.197225
15	8.55	2.197225
16	8.55	2.197225
17	8.53	1.098612
18	8.53	1.098612
19	8.55	2.197225
20	8.55	2.197225
21	8.55	2.197225

Appendix 22 . Dissolved Oxygen Reading vs Time for Qg= 20 L/min, N=300 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.47	0
1	8.47	0
2	8.53	1.098612
3	8.53	1.098612
4	8.54	1.504077
5	8.54	1.504077
6	8.54	1.504077
7	8.54	1.504077
8	8.54	1.504077
9	8.55	2.197225
10	8.55	2.197225
11	8.55	2.197225
12	8.55	2.197225
13	8.55	2.197225
14	8.55	2.197225
15	8.55	2.197225
16	8.55	2.197225
17	8.53	1.098612
18	8.53	1.098612
19	8.55	2.197225
20	8.55	2.197225
21	8.55	2.197225

Appendix 23 . Dissolved Oxygen Reading vs Time for Qg= 25 L/min, N=220 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	10.27	0
1	10.36	0.223144
2	10.44	0.474458
3	10.44	0.474458
4	10.46	0.548566
5	10.52	0.81093
6	10.52	0.81093
7	10.53	0.862224
8	10.53	0.862224
9	10.53	0.862224
10	10.55	0.973449
11	10.56	1.034074
12	10.57	1.098612
13	10.57	1.098612
14	10.57	1.098612
15	10.59	1.241713
16	10.59	1.241713
17	10.59	1.241713
18	10.62	1.504077
19	10.63	1.609438
20	10.63	1.609438
21	10.65	1.860752
22	10.65	1.860752
23	10.65	1.860752
24	10.65	1.860752
25	10.65	1.860752
26	10.67	2.197225
27	10.69	2.70805
28	10.69	2.70805
29	10.71	3.806662
30	10.71	3.806662
31	10.71	3.806662

Appendix 24 . Dissolved Oxygen Reading vs Time for Qg= 25 L/min, N=280 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	10.6	0
1	10.59	-0.09531
2	10.58	-0.18232
3	10.58	-0.18232
4	10.56	-0.33647
5	10.54	-0.47
6	10.54	-0.47
7	10.54	-0.47
8	10.54	-0.47
9	10.54	-0.47
10	10.54	-0.47
11	10.54	-0.47
12	10.55	-0.40547
13	10.55	-0.40547
14	10.55	-0.40547
15	10.55	-0.40547
16	10.53	-0.53063
17	10.53	-0.53063
18	10.55	-0.40547
19	10.55	-0.40547
20	10.55	-0.40547
21	10.55	-0.40547
22	10.5	-0.69315
23	10.51	-0.64185

Appendix 25 . Dissolved Oxygen Reading vs Time for Qg= 25 L/min, N=300 rpm

Time(minute)	Dissolved Oxygen (mg/L)	-ln((Cair-C)/(Cair-Cin))
0	8.18	0
1	8.65	3.871201
2	8.65	3.871201
3	8.63	2.772589
4	8.55	1.473306
5	8.53	1.306252
6	8.51	1.163151
7	8.49	1.037988
8	8.49	1.037988
9	8.47	0.926762
10	8.47	0.926762
11	8.47	0.926762
12	8.47	0.926762
13	8.47	0.926762
14	8.47	0.926762
15	8.49	1.037988
16	8.54	1.386294
17	8.54	1.386294
18	8.54	1.386294
19	8.5	1.098612
20	8.5	1.098612
21	8.5	1.098612
22	8.48	0.980829
23	8.64	3.178054
24	8.64	3.178054
25	8.65	3.871201
26	8.65	3.871201
27	8.65	3.871201